The Next-to-Minimal Supersymmetric Standard Model

U. Ellwanger, LPT Orsay

Why Supersymmetry?

The origin of the electroweak scale $M_{weak} \sim 100$ GeV
– the only explicit mass scale in the Standard Model –
could also be explained by

— new strong interactions at ~ 1 TeV
— compact extra dimensions
— in Susy: $M_{weak} \sim$ Susy breaking scale M_{Susy}
  = scale of masses of Higgs bosons, squarks, sleptons, gauginos
— ONLY with Susy: the ratios of the 3 gauge couplings are explained by simple (SU(5), SO(10)) Grand Unification at a reasonable scale $10^{16}\text{GeV} < M_{GUT} < 10^{17}\text{GeV}$!

The Higgs sector in supersymmetric extensions of the Standard Model

At least two SU(2) doublets H_u, H_d:

H_u couples to up-type quarks

H_d couples to down-type quarks and leptons

Soft Susy breaking mass terms $m^2_{H_u}$, $m^2_{H_d}$ (with $m^2_{H_u} < 0$ naturally through radiative corrections, if $m_{top} > 60$ GeV) trigger $\langle H_u^0 \rangle$, $\langle H_d^0 \rangle \neq 0$ ✓

Physical states (− Goldstone bosons):

2 CP-even neutral scalars h, H

1 CP-odd neutral scalar A

1 charged scalar $H^\pm$

4 neutralinos, 2 charginos

One linear combination of h, H (typically h) couples to the gauge bosons similar to the Standard Model Higgs boson

Masses and couplings depend on undetermined parameters like
$m^2_{H_u}$, $m^2_{H_d}$ $\longleftrightarrow$ $\tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$, m_A, squark masses (via rad. corrs.), ...

For $m_A \gg M_Z$: the extra Higgs states
H, A and $H^\pm$ form a (nearly degenerate) SU(2) multiplet of mass $\sim m_A$

However:

— The lightest CP-even scalar h has a mass below $\sim$ 135 GeV

— Its detection at the LHC is guaranteed within $\sim$ 3 years in one or the other production/decay mode (if an integrated luminosity of 30 fb^{-1} and a c.m. energy of 14 TeV are achieved):

"No-loose Theorem"

Note: a light Higgs ($m_h \lesssim$ 120 GeV) is not easier to detect at the LHC!

Why extend the Higgs sector of the MSSM?

— the charged fermionic superpartners of $H_{u,d}$ mix with the charged SU(2) gauginos to form two (Dirac-) charginos

— LEP II: the lightest chargino is heavier than 103 GeV

$\longrightarrow$ a (supersymmetric) mass term $|\mu| \gtrsim 100$ GeV for the higgsinos is necessary (this is not a Susy breaking parameter!)

$\longrightarrow$ spoils a nice relation: $M_{weak} \sim M_{Susy}$ with M_{Susy} as the only dimensionful parameter (below the Planck/GUT scale)

$\longrightarrow$ "μ–problem": why is a supersymmetric mass term of the order of the Susy breaking scale (Kim, Nilles)?

$\longrightarrow$ generate (supersymmetric) higgsino masses via a Yukawa coupling to a field S with $\langle S \rangle \neq 0$
(the first Susy/Sugra models by Fayet, Sakai, Witten, Nilles,... included such a gauge singlet superfield)

$\longrightarrow$ this is the Next-to-Minimal Supersymmetric Standard Model (NMSSM); gauge coupling unification is preserved!

Superpotential of the NMSSM:

$W_{MSSM} = \mu H_u H_d + \ldots \longrightarrow W_{NMSSM} = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \ldots$ (scale inv.)

Hence: $\mu \psi_u \psi_d + \ldots \longrightarrow \lambda S \psi_u \psi_d + \ldots$

$\langle S \rangle \neq 0$ easy to achieve with the help of a negative Susy breaking mass term (and/or a trilinear self coupling) for $S \longrightarrow \langle S \rangle \sim M_{Susy}$

$\longrightarrow \mu_{\text{eff}} = \lambda \langle S \rangle \sim M_{Susy}$ automatically ✓

Physical states:

3 CP-even neutral scalars H_i
2 CP-odd neutral scalars A_i
1 charged scalar $H^{\pm}$
5 neutralinos, 2 charginos

This does not necessarily simplify the detection of at least one Higgs boson!

— more (5 instead of 2) undetermined parameters in the Higgs sector; in some regions of parameter space (small λ), the NMSSM will be very difficult to distinguish from the MSSM. In other regions of parameter space, important phenomenological differences can appear:

1) the SM-like CP-even scalar can be $\sim$ 15 GeV heavier than in the MSSM

2) the singlet-like CP-even scalar can mix with the SM-like CP-even scalar, and have a mass below 114 GeV (allowed by LEP!)

3) the singlet-like CP-odd scalar A_1 can be light
$\longrightarrow$ the SM-like CP-even scalar h can decay dominantly as
$h \to A_1 A_1 \to 4b,\ 2b2\tau,\ 4\tau \ldots$ depending on M_{A_1}

$\longrightarrow$ LEP constraints easier to satisfy

Lessons/Hints from LEP

Search for $H \to b\bar{b}$, $\tau^+\tau^-$ (comb. 4 exp., LEP-Higgs Working Group):

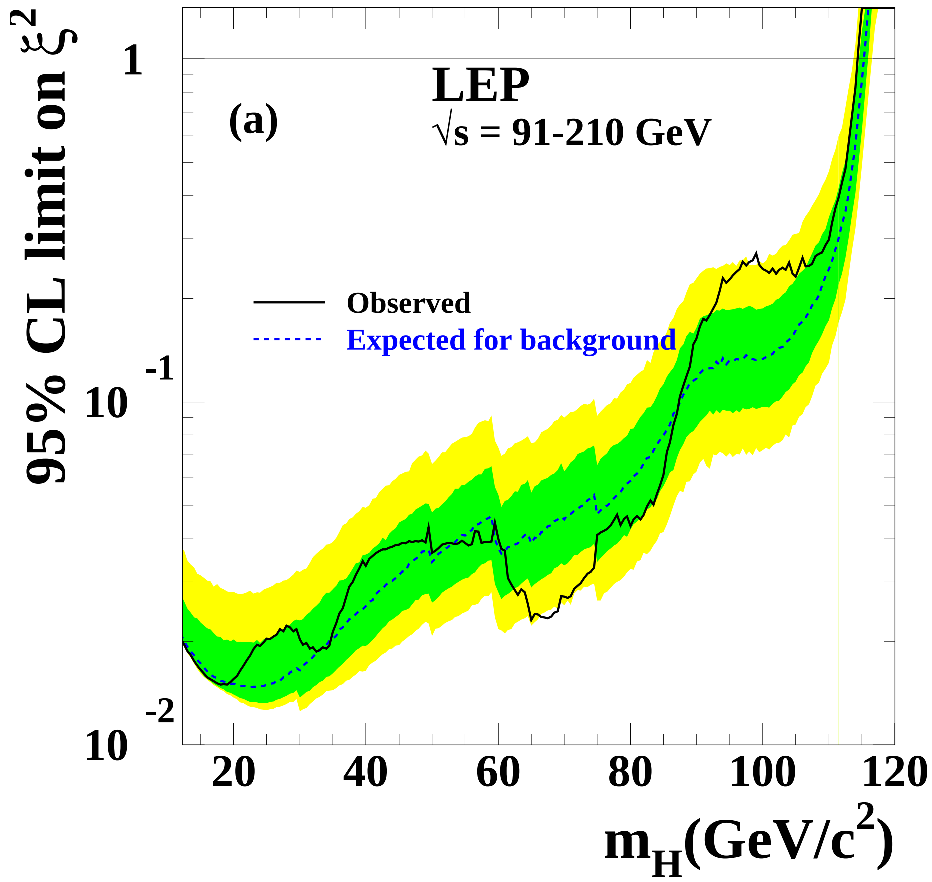
Light excess of events for $m_H \sim 95 - 100$ GeV ($\sim 2.3\,\sigma$)

If such an H exists, it must possess:

$\longrightarrow$ Either a reduced coupling $g_{HZZ}/g_{HZZ\_SM} \equiv \xi \lesssim 0.4 - 0.5$

$\longrightarrow$ or a reduced BR to $b\bar{b}$: $BR(H \to b\bar{b})/BR_{SM} \lesssim 0.2$

$\longrightarrow$ $BR(H \to A_1 A_1) \sim 80 - 90\%$?
(Dermisek, Gunion: solution of the "little finetuning problem" of the MSSM)



Search for $H \to A_1 A_1$ at LEP:

- $\longrightarrow$ Strong bounds on $H \to A_1 A_1 \to 4b$ for $m_H \sim 95 - 100$ GeV (OPAL, DELPHI)
- $\longrightarrow$ M_{A_1} below $B\bar{B}$ threshold: $M_{A_1} < 2M_B \sim 10.5$ GeV
- $\longrightarrow$ A_1 decays dominantly into $A_1 \to \tau^+ \tau^-$
- $\longrightarrow$ Searches for $H \to A_1 A_1 \to 4\tau$:
  (preliminary) bounds from ALEPH for $m_H \sim 95 - 100$ GeV;
  Dermisek, Gunion: still OK if $BR(A_1 \to \tau^+ \tau^-) \sim 80\%$ (small $\tan\beta$)

Constraints from Υ-decays (and CDF on $A_1 \to \mu^+ \mu^-$):

$M_{A_1} \gtrsim 9$ GeV, or $A_1\, b\bar{b}$ - coupling small (see the talk by F. Domingo)

For dominant $H \to A_1 A_1 \to 4\tau$: Higgs search at the LHC will be difficult!

— 4 neutrinos (at least), no narrow peaks in invariant masses;
— 2 τ's (of the same A_1) nearly collinear, low invariant masses, low p_T;
— Backgrounds: Υ production, heavy flavour jets, . . .

Forshaw et al. (0712.3510): via diffractive Higgs Production $pp \to pp + H$
($\to$ additional forward proton detectors at ATLAS and/or CMS)
Belyaev et al. (0805.3505, 1002.1956):
via $A_1 A_1 \to 4\tau \to 2\mu + 2$ jets, or $A_1 A_1 \to 4\tau \to 4\mu$

Or: use subdominant A_1 decays:
$BR(A_1 \to \mu^+\mu^-) \sim 3 \cdot 10^{-3}$ would be clean
($BR(A_1 \to \gamma\gamma) \lesssim 10^{-4}$ would be too low)
Lisanti, Wacker (0903.1377): $A_1 A_1 \to 2\tau + 2\mu$ from H via gg fusion

Current ATLAS studies: $A_1 A_1 \to 4\tau \to 4\mu$ (VBF)
Current CMS studies: $A_1 A_1 \to 4\tau \to 2\mu + 2$ jets (HS)

Due to the extended neutralino sector of the NMSSM:

The LSP can be the additional singlino-like neutralino $\chi_1^0 \sim \chi_S$ (weakly mixed with the bino,...)

cNMSSM: Universal soft Susy breaking scalar masses m_0 + trilinear couplings A_0 + gaugino masses $M_{1/2}$ at the GUT/Planck scale, as in minimal supergravity (A. Djouadi, U.E., A. Teixeira)

$\longrightarrow$ the LSP is always the singlino-like neutralino, with a mass just a few GeV below the NLSP = stau $\tilde{\tau}$
($\rightarrow$ good relic density due to co-annihilation with the stau)

$\longrightarrow$ $m_0 \sim 0$, $A_0 \sim -\frac{1}{4} M_{1/2}$, essentially 1 undetermined parameter $M_{1/2}$

Possibly: A singlet-like CP-even Higgs scalar with a mass ~ 100 GeV (recall the "bump" at LEP...)

Implications for sparticle searches at the LHC:

Typical squark decay cascades:

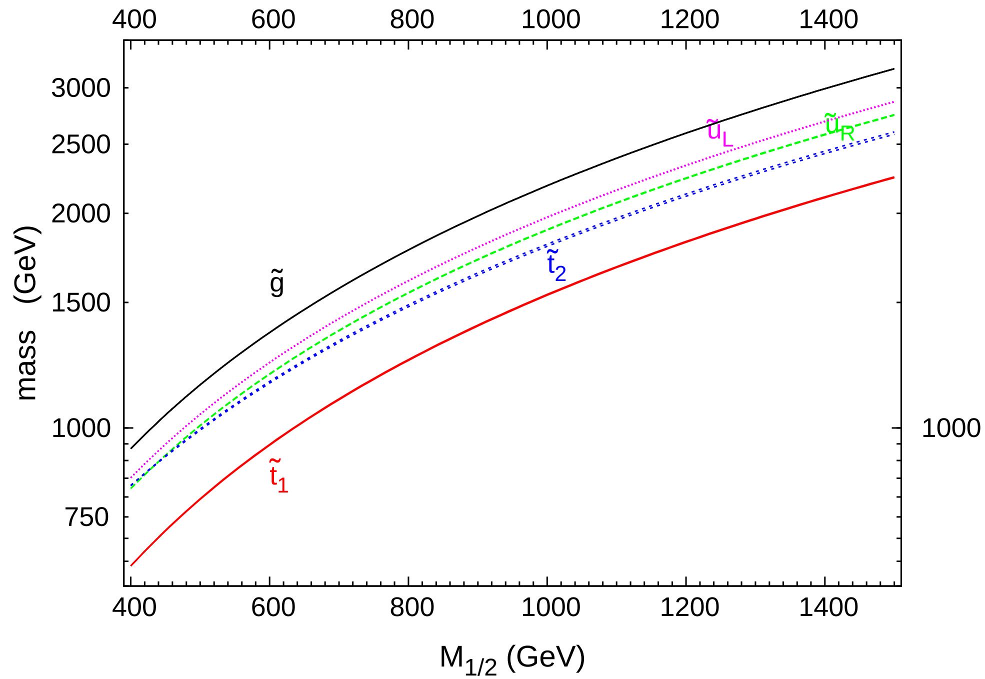
$$\tilde{q} \to q + \chi_2^0(\text{bino}) \to q + \tau + \tilde{\tau} \to q + \tau + \tau + \chi_1^0(\text{singlino})$$

$\longrightarrow$ Mostly 2 τ's per squark decay cascade (one hard, one soft)!

But: The last decay $\tilde{\tau} \to \tau + \chi_1^0$ may take a while
(since $m_{\tilde{\tau}} - m_{\chi_1^0} \lesssim$ a few GeV from Ω_{DM} on top of a small coupling)

$\longrightarrow$ possibly displaced vertices from stau decays (mm – cm)!

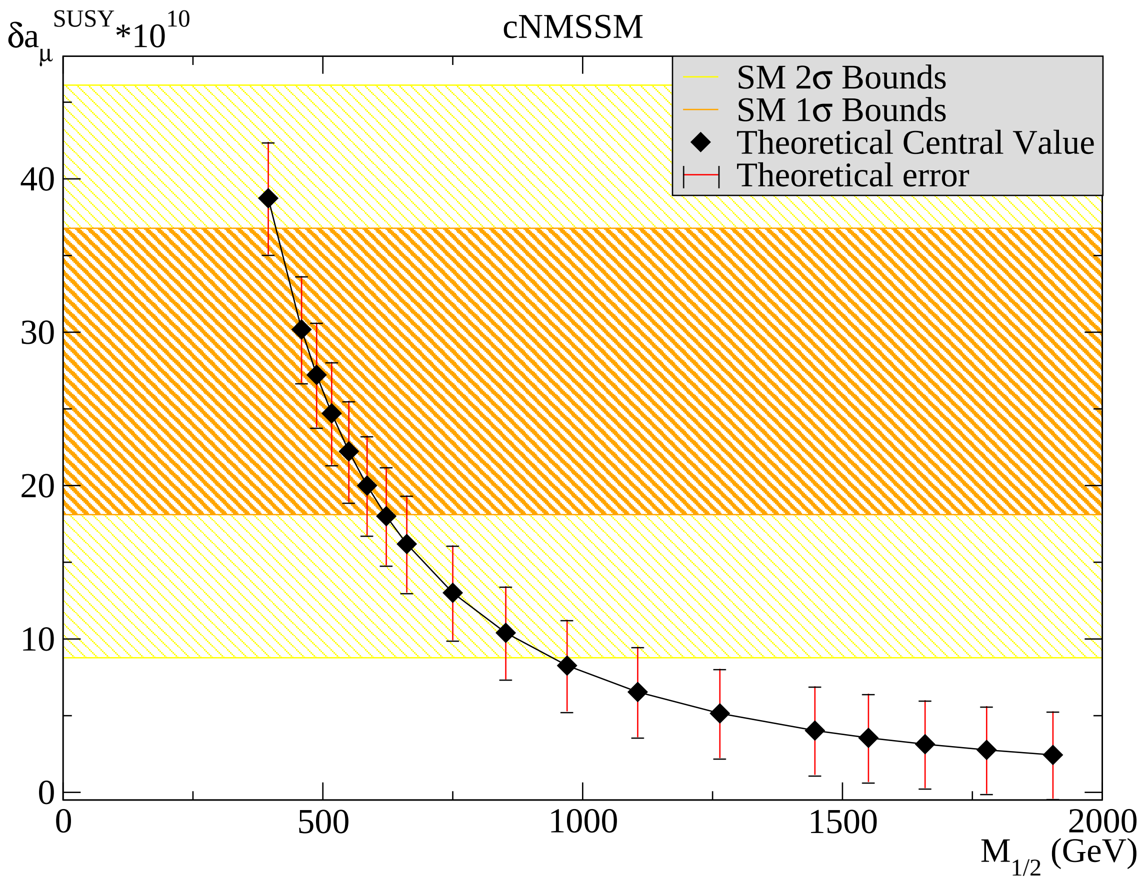
Squark and gluino masses as function of $M_{1/2}$



$\longrightarrow$ gluino heavier than squarks,

$\longrightarrow$ for $M_{1/2} \gtrsim 500$ GeV: no conflict with any sparticle searches (or B-physics, Higgs searches at LEP, ...)

Muon anomalous magnetic moment:



Require a Susy contribution to the anomalous magnetic moment of the muon, in order to explain the present 3σ discrepancy in the SM (U. E., F. Domingo) $\longrightarrow M_{1/2} \lesssim 1$ TeV (~ 500 GeV?)

Visible at the LHC?

For $M_{1/2} \sim 500$ GeV: $M_{gluino} \sim 1.2$ TeV, $M_{squarks} \sim 1$ TeV
$\longrightarrow$ no signal (~ 10 events/fb^{-1}) at 7 TeV c.m. energy
$\longrightarrow$ only ~ 1000 events/fb^{-1} at 14 TeV c.m. energy

$\longrightarrow$ Dedicated cuts (with T. Plehn, preliminary):
2 jets with $p_T > 300/150$ GeV, $E_T(miss) > 200$ GeV,
require a hadronically decaying τ with p_T(visible remnants) > 40 GeV
(Further standard cuts on $\Delta\phi$(jets$-E_T(miss)$), M_T)

Assume a τ acceptance of $\sim 30 - 40\%$
$\longrightarrow$ Signal acceptance: $\gtrsim 10\%$ ($\gtrsim 100$ events/fb^{-1})
$\longrightarrow$ Background acceptance ($t\bar{t}$): $\sim 10^{-5}$ (~ 8 events/fb^{-1})

$\rightarrow$ Looks promising!

(Difference w.r.t. stau-coannihilation-region of the cMSSM:
harder spectrum of $p_T(\tau)$, since mostly 2 hard τ's per event)

Conclusions

— the NMSSM can be considered as the most natural supersymmetric extension of the Standard Model:
no μ-problem, scale invariant superpotential, $M_{weak} \simeq M_{Susy}$

— Larger parameter space, constraints from LEP easier to satisfy:
either heavier h, or $h \to A_1 A_1$; difficult for the LHC:
studies are under way, but no "No-loose-theorem" at present $\longrightarrow$
"No Higgs" at the LHC can be a signal of the NMSSM!

— Case of a singlino-like LSP (like in the cNMSSM):
important effects on sparticle searches:
- ~ 4 τ's per Susy event
- possibly displaced vertices from stau-decays!